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RING CORE FIBER

Cross-Reference to Related Applications

[001] This application is a continuation-in part of International Application No. PCT/US02/09513, which has an international filing date of March 27, 2002, and is entitled "Ring Core Fiber", and which in turn claims priority to United States Provisional Patent Application Serial No. 60/280,033, which was filed March 30, 2001 and is also entitled "Ring Core Fiber". The foregoing applications are incorporated herein by reference.

Technical Field

[002] The invention relates to optical waveguides, such as, for example, optical fibers, and to amplifiers and lasers that include optical waveguides, such as for example, fiber lasers and fiber amplifiers, and to systems including such amplifiers and lasers.

Background

[003] Fibers, such as fiber lasers and fiber amplifiers, can be used to enhance absorption of pump energy. One type of fiber, commonly referred to as a double clad fiber, includes

a core, a first cladding around the core and a second cladding around the first cladding. The core can comprise a rare earth material. The first cladding can be capable of receiving pump energy for absorption by the rare earth material. The second cladding can tend to prevent the pump energy from escaping the first cladding.

Summary

[004] The invention typically relates to optical fibers, fiber lasers and fiber amplifiers, and to systems including such fibers and fiber devices.

[005] In one aspect, the invention features a fiber (e.g., a multimode fiber) that includes a first region, a core and a cladding. The core surrounds the first region, and the cladding surrounds the core. Typically, the core includes an active material, such as, for example, a selected rare earth material.

[006] In a further aspect, the invention features a system that includes two fibers. One of the fibers has a first region, a first core (e.g., a multimode core) surrounding the first region, and a cladding surrounding the core. The other fiber has a core (e.g., a single mode core). The fibers are in optical communication (connected) such that energy can propagate from the core of one fiber to the core of the other fiber. Typically, at least one of the cores includes an active material.

[007] Embodiments of the invention can include one or more of the following features.

[008] The core can be ring-shaped.

[009] The core can be a multimode core.

[010] The core can include a rare earth-doped material.

[011] The core can include a silica material and ions of a rare earth metal.

- [012] The first region can include a silica material.
- [013] The first region can have a lower index of refraction than the core.
- [014] The first cladding can include a silica material.
- [015] The first cladding can have a lower index of refraction than the core.
- [016] The fiber can further include a second cladding surrounding the first cladding.
- [017] The second cladding can be formed of a polymer material.
- [018] The index of refraction of the first cladding can be greater than the index of refraction of the second cladding.
- [019] The fiber can be a multimode fiber.
- [020] The system can include one or more additional fibers. Each of the additional fiber(s) can individually be a single mode fiber or a multimode fiber. The core of each of the additional fiber(s) can individually be in optical communication with the first core so that energy can propagate from the core to the particular additional fiber, or, alternatively or additionally, from the particular fiber to the core. The particular additional fiber can be connected to the fiber, such as by being spliced to the fiber. A lens or system of lenses can be used for optical communication.
- [021] The system can further include an energy source.
- [022] The system can further include a coupler configured to couple energy emitted by the energy source to the core.
- [023] In certain embodiments, the fiber provides the advantage of being a multimode

fiber. This can be advantageous, for example, when it is desirable to propagate a relatively high amount of energy through a relatively small amount of space. In some embodiments, the fiber is designed to be scalable. For example, the fiber can be designed so that, as its length is increased, the amount of energy (power) that can be propagated by the fiber increases (e.g., increases approximately linearly).

[024] In some embodiments, the fiber can be designed to have a core capable of absorbing a relatively large amount of energy per unit length of fiber. In some embodiments, relative to other fibers having the same total cross-section, the fiber of the invention can have increased pump energy absorption.

[025] In certain embodiments, the fiber can be designed to have a relatively large effective cross-sectional area. In some embodiments, this can reduce undesirable nonlinear effects.

[026] In some embodiments, the fiber can be designed to be used in a side pump configuration and/or an end pump configuration.

[027] In certain embodiments, a fiber can be relatively easily manufactured.

[028] In some embodiments, a fiber can exhibit enhanced absorption. In certain embodiments, this can result from a fiber having a relatively large effective area.

[029] In some embodiments, a fiber can exhibit relatively high stability. In certain embodiments, this can result from a fiber having a relatively short cavity length.

[030] In some embodiments, a fiber can exhibit relatively few non-linear effects. In certain embodiments, this can result from a fiber having a relatively low power density.

[031] In some embodiments, systems can be relatively easily developed by adding more sections. In certain embodiments, this can result from the relatively easy power scaling

properties of a fiber.

[032] Features, objects and advantages of the invention are in the summary, description, drawings and claims.

Description Of Drawings

[033] Fig. 1 is a cross-sectional view of an embodiment of a fiber;

[034] Fig. 2A is a cross-sectional view of the fiber of Fig. 1;

[035] Fig. 2B is an index profile of the fiber of Figs. 1 and 2A;

[036] Fig. 3 is a perspective view of an embodiment of a fiber;

[037] Fig. 4 is a graph of the self-image length as a function of inverse wavelength for an embodiment of a fiber;

[038] Fig. 5 is a cross-sectional view of an embodiment of a system including a fiber;

[039] Fig. 6 is a cross-sectional view of an embodiment of a system including a fiber;

[040] Fig. 7 is a cross-sectional view of an embodiment of a system including a fiber;
and

[041] Fig. 8 is a graph of the self image length and double self image length as a function of radius for an embodiment of a fiber.

Detailed Description

[042] Figs. 1 and 2A show cross-sectional views of an embodiment of a fiber **10** having a first region **12**, a ring-shaped core **14**, a first cladding **16** and a second cladding **18**.

[043] Typically, core 14 includes a first material (e.g., a silica material, such as a fused silica) and at least one dopant (e.g., at least one rare earth ion, such as, for example, erbium ions, ytterbium ions, neodymium ions, holmium ions, dysprosium ions and/or thulium ions; and/or transition metal ion(s)) where the rare earths are understood to include elements 57-71 of the periodic table. More generally, however, core 14 can be formed of any material (e.g., active material) or combination of materials (e.g., active materials) capable of interacting with a pump signal to enhance pump signal absorption (e.g., produce gain). In certain embodiments, core 14 is formed of fused silica doped with erbium ions. As is well understood by one of ordinary skill in the art, active materials, such as the rare earths, provide energy of a first wavelength responsive to receiving energy (typically referred to as “pump” energy) of a second wavelength that is different than the first wavelength.

[044] Core 14 can optionally include certain other materials. For example, core 14 can include one or more materials to increase the index of refraction. Such materials include, for example, germanium oxide. Core 14 can include one or more materials to decrease the index of refraction. Such materials include, for example, boron oxide. Core 14 can include one or more materials (e.g., aluminum oxide) that enhance the solubility of the rare earth ion(s) within core 14 (e.g., within silica, such as fused silica). Core 14 can include one or more materials that enhance the homogeneity of the index of refraction within core 14. An example of such a material is phosphorus pentoxide.

[045] Generally, core 14 is designed to support multimode energy propagation. The thickness R of core 14 can vary depending upon the intended use of fiber 10. In certain embodiments, the thickness R of core 14 is less than about 15 microns (e.g., less than about 10 microns, less than about nine microns, less than about eight microns, less than about seven microns, less than about six microns, less than about five microns). In some embodiments, the thickness R of core 14 is at least about one micron (e.g., at least about two microns, at least about three microns, at least about four microns). In certain embodiments, the thickness R of core 14 is from about four microns to about five microns.

[046] Region 12 is usually formed of a material having a lower refractive index than core 14. In some embodiments, core 14 has a refractive index (n_{14}) and region 12 has a refractive index (n_{12}) so that $((n_{14})^2 + (n_{12})^2)^{1/2}$ is less than about 0.2 (e.g., less than about 0.17) and greater than about 0.05 (e.g., greater than about 0.12), such as from about 0.12 to about 0.17. Examples of materials from which region 12 can be formed include silica materials, such as fused silica materials. In certain embodiments, the refractive index of region 12 is about the same (e.g., the same) as the refractive index of core 14.

[047] Cladding 16 usually comprises a lower refractive index than core 14. In some embodiments, core 14 has a refractive index (n_{14}) and cladding 16 has a refractive index (n_{16}) so that $((n_{14})^2 + (n_{16})^2)^{1/2}$ is less than about 0.2 (e.g., less than about 0.17) and greater than about 0.05 (e.g., greater than about 0.12), such as from about 0.12 to about 0.17. Examples of materials from which cladding 16 can be formed include silica materials, such as fused silica materials. In some embodiments, region 12 and cladding 16 are formed of the same material(s). In certain embodiments, region 12 and cladding 16 are formed of different material(s).

[048] Cladding 18 usually comprises a lower refractive index than an index of refraction comprised by cladding 16. In some embodiments, claddings 18 and 16 have refractive indices (n_{18}) and (n_{16}), respectively, so that $((n_{18})^2 + (n_{16})^2)^{1/2}$ is less than about 0.6 (e.g., less than about 0.5) and greater than about 0.3 (e.g., greater than about 0.4), such as from about 0.42 to about 0.47. Examples of materials from which cladding 18 can be formed include polymeric materials, such as, for example, acrylate resins, silicone polymers, polyurethane. Such materials can be, for example, fluorinated or nonfluorinated. Cladding 16 and 18 can also comprise microstructured-type claddings, and can, for example, comprise voids or air or another gas. Microstructured claddings, as is well known in the art, can comprise photonic bandgap structures or structures that achieve a selected average index of refraction, such as by, for example, incorporating gaps or voids.

[049] Fig. 2B is a refractive index profile of fiber 10 in an embodiment in which section 13 of the refractive index profile corresponds generally to the region 12; sections 15

correspond generally to the core 14; sections 17 correspond generally to the first cladding 16; and sections 19 correspond generally to the second cladding 18. In the embodiment shown, the refractive index of core 14 is greater than the refractive indices of region 12, cladding 16 and cladding 18; the refractive index of region 12 is about the same as the refractive index of cladding 16; and the refractive index of cladding 18 is less than the refractive index of region 12 and the refractive index of cladding 16. Typically, but not necessarily, one or more of the region 12, the core 14 and the cladding 16 and 18 each comprise a single refractive index that is substantially constant.

[050] Fig. 3 illustrates the manner in which energy can propagate along fiber 10 (cladding 18 not shown). Energy focused at a point 30 on core 14 is focused at its mirror image point 32 on core 14 after propagating along core 14 for a distance L. After the energy propagates along core 14 another distance L, the energy is focused at a point 34 of core 14, which is the self image of point 30 on core 14. It is therefore possible to use fiber 10 for relatively high power transmission via fiber 10. This can be advantageous, for example, when it is desirable to use a relatively short length of fiber to transmit a relatively high power (e.g., when decreasing the length of fiber results in more stable and/or higher quality signal transmission).

[051] Without wishing to be bound by theory, it is believed that this behavior can be explained through multimode interference phenomena as follows. An arbitrary energy distribution $A(r, \theta)$ in the object plane of an endface 35 of fiber 10 can be represented as a superposition of all waveguide modes:

$$A(r, \theta) = \sum a_m F_m(r, \theta)$$

where a_m are the complex amplitude coefficients (time factor $e^{-i\omega t}$ omitted). After propagating through a distance z , the energy distribution becomes:

$$B(r, \theta) = e^{i\beta_0 z} \sum a_m F_m(r, \theta) e^{i\varphi_m}$$

where $\varphi_m = (b_m - b_0)z$ is the phase difference between the m^{th} and fundamental mode ($m=0$). A good approximation yields:

$$\varphi_m \cong \pi m^2 z L_1 = -\pi m^2 h$$

where $L_1 = (N^2 \pi R)/\lambda$ is the effective index of the equivalent planar waveguide to fiber

10.

[052] At a distance $z = L(h=1)$, then $B(r, \theta) = A(r, \theta + \pi)$, which is the mirror image signal. The simplest multiple image is at $h = 1/2$, where $B(r, \theta) = ((1-i)/2)A(r, \theta) + ((1+i)/2)A(r, \theta + \pi)$, which corresponds to the self image signal. Higher order signals can be formed in an analogous way.

[053] Fig. 4 is a graph of calculated values using the above equations for the self image length as a function of the inverse of wavelength of the energy (e.g., light) for a double clad fiber as shown in Figures 1 and 2A with a core radius of 33.5μ and a core radius of 66μ (calculations assume no change in refractive index caused by the pump energy). The data for a core radius of 33.5μ is scaled by a factor of 3.88, which is the square of the ratio of the radii (i.e. $(66/33.5)^2$). Fig. 4 shows that, for a given ring core radius, the self image length is substantially directly proportional to the inverse of the wavelength of the energy (the data for 33.5μ ring core radius had an R value of 0.9999, and the data for the 66μ ring core radius had an R value of 0.99998). Fig. 4 also shows that, for a given wavelength of energy, the self image length scales as the square of the ring core radius.

[054] With this information, the ring core radius, wavelength of energy and/or self image length for a double clad fiber as shown in Figs. 1 and 2A can be manipulated in a relatively predictable fashion. Generally, if the self-image length for such a fiber is known at a given wavelength of energy and ring core radius, one of these parameters can be varied in a predictable fashion when the other two variables are kept constant. As an example, if the self image length for such a fiber is known at a given wavelength of energy and ring core radius, the appropriate self image length can be determined *a priori* when the ring core radius is varied and the wavelength of energy is kept constant. As another example, if the self image length for such a fiber is known at a given wavelength of energy and ring core radius, the appropriate wavelength of energy can be determined *a priori* when the self image length is varied and the ring core radius is kept constant. As a further example, if the self image length for such a fiber is known at a given wavelength of energy and ring core radius, the appropriate ring core radius can be determined *a priori*

when the wavelength of energy is varied and the self image length is kept constant. Other examples will be apparent to those skilled in the art.

[055] Fig. 5 shows a fiber laser system 40 in which fiber 10 is used as a gain medium. An energy source 42 emits a pump signal 44 which is coupled to fiber 10 via a coupler 46 (e.g., a V-shaped groove, such as a 90° V-shaped groove, cut into claddings 16 and 18 on the side of fiber 10; a removed portion of cladding 18 that is replaced with a prism having substantially the same refractive index as cladding 16; a removed portion of cladding 18 that is replaced with a coupling window; or the like).

[056] A single mode fiber 48 having a core 47, a cladding 45 and a reflective element 87 (e.g., a grating) optically communicates with at least (or only) a part of the cross section of the core 14 at one end of fiber 10, as indicated by Fig. 5. Core 47 is connected to core 14 in Fig. 5. A single mode fiber 50 having a core 49, a cladding 51 and a reflective element 85 (e.g., a grating) optically communicates with the core 14 at a different end of fiber 10 so that core 49 is connected to core 14. Fiber 48 can be a passive single mode fiber or an active single mode fiber, and fiber 50 can be a passive single mode fiber or an active single mode fiber. Typically, in embodiments in which fibers 48 and 50 are passive single mode fibers, cores 47 and 49 are formed of silica (e.g., fused silica) and one or more materials (e.g., germanium), and claddings 45 and 51 are formed of silica (e.g., fused silica). Examples of single mode fibers are known to those skilled in the art and are contemplated. Generally, in embodiments in which fibers 48 and 50 are active single mode fibers, cores 47 and 49 are formed of silica (e.g., fused silica) and an active material, and claddings 45 and 51 are formed of silica (e.g., fused silica). Examples of active single mode fibers are disclosed, for example, in "Rare Earth Doped Fiber Lasers and Amplifiers", edited by Michael J.F. Digonnet (1993), which is hereby incorporated by reference.

[057] Typically, the dimensions of fibers 48 and 50 are selected so that there is good mode matching between core 14 and cores 47 and 49. In some embodiments, this can be achieved by selecting cores 47 and 49 to have a diameter that is substantially the same

size as a thickness of the core 14, as shown in Fig. 5.

[058] Fiber 10 can have a length L so that the respective positions at which the single mode cores of fibers 48 and 50 are connected to core 14 are diametrically opposed (mirror image). Fibers 48 and 50 have elements 87 and 85, respectively. Elements 87 and 85 are designed to reflect energy at a desired wavelength (λ_{out}). Cores 14, 47 and 49 include one or more materials (e.g., active material(s)) that interact(s) with the pump signal so that elements 87 and 85 provide a lasing cavity for energy at λ_{out} and fiber 10 acts as a gain medium for energy at λ_{out} . In certain embodiments, the reflectance (e.g., less than 100%) of element 87 for energy at λ_{out} is substantially less than the reflectance (e.g., about 100%) of element 85 for energy at λ_{out} so that a portion of the energy at λ_{out} passes through element 85. While shown in Fig. 5 as having a length L , fiber 10 in system 40 can more generally have any odd integer length of L (e.g., $3L$, $5L$, $7L$, $9L$, $11L$, etc.) while maintaining the relative positions of fibers 48 and 50 unchanged (e.g., diametrically opposed).

[059] Fig. 6 shows a fiber laser system 60 in which fiber 10 is used as a gain medium and has a length $2L$. In this embodiment, the respective positions at which the single mode cores of fibers 48 and 50 are connected to core 14 are a self image. While shown in Fig. 6 as having a length $2L$, fiber 10 in system 60 can more generally have any even integer length of $2L$ (e.g., $4L$, $6L$, $8L$, $10L$, etc.) while maintaining the relative positions of fibers 48 and 50 unchanged (e.g., self image configuration).

[060] Fig. 7 shows a fiber system 70 in which fiber 10 is used as a gain medium. The core of single mode fiber 48 optically communicates with (is connected to) core 14 at one end of fiber 10, and the other end of fiber 10 is coated with a reflective material 72 (e.g., a mirror, such as a broad band mirror) so that element 87 and mirror 72 provide a lasing cavity for energy λ_{out} and fiber 10 acts as a gain medium for energy at λ_{out} . In these embodiments, mirror 72 can reflect substantially all (e.g., about 100%) of the energy at λ_{out} , and element 87 can reflect less (e.g., less than about 100%) of the energy at λ_{out} so that a portion of the energy at λ_{out} passes through element 87. In these embodiments,

can have a length that is an integer number of L (e.g., L , $2L$, $3L$, $4L$, $5L$, $6L$, etc.), or fiber 10 can have a length that is not an integer number of L .

[061] While Figs. 5-7 show certain embodiments of fiber 10 in a fiber laser system, other arrangements will be apparent to those skilled in the art. For example, fiber 10 can be used in fiber amplifier systems and/or systems that include both fiber lasers and fiber amplifiers. Examples of fiber laser systems and fiber amplifier systems in which fiber 10 can be used are disclosed, for example, in commonly owned U.S. Provisional Patent Application Serial No. 60/267,252 filed on February 7, 2001, and entitled "Raman Fiber Laser" and in commonly owned U.S. Patent Application Serial No. 09/798,148, filed on March 2, 2001, and entitled "Fiber For Enhanced Energy Absorption" (now issued as U.S. Patent 6,516,124 on February 4, 2003), both of which are incorporated by reference herein.

[062] While certain embodiments of the invention have been disclosed herein, the invention is not limited to these embodiments. For example, in certain embodiments, the fiber 10 can have any design appropriate to support multimode energy propagation. For example, fiber 10 can include multiple ring-shaped cores. It may be desirable in such embodiments for the length of fiber 10 to be selected so that it matches the self image lengths or integer multiples thereof for the ring-shaped cores. Using the above equations, the length of fiber 10 can be calculated *a priori* to achieve this goal. An example of such a calculation is as follows. Fig. 8 shows a graph of the first self image length (lower curve) and second self image length (upper curve) as a function of the ring core radius for a double clad fiber having a ring core radius containing active material. With this information, for example, the appropriate length of a fiber having two concentric ring cores containing active material can be determined so that the length of the fiber corresponds to twice the self image length of the inner core and the self image length of the outer core, resulting in both the inner and outer rings of the fiber being capable of being used as a gain medium. This can be achieved, for example, as follows. A radius for the inner ring is selected, and its double self image length is determined based upon the point (point A) on the upper graph in Fig. 8 that has the same radius. A radius for the

outer ring is then determined based upon the point (point B) on the lower graph in Fig. 8 that has the same self image length as point A. Other techniques of selecting appropriate fiber lengths for a given number of ring cores will be apparent to those skilled in the art.

[063] The shapes and sizes of the elements of fiber 10 can also be varied as desired. Examples of certain appropriate fiber designs, shapes and sizes are disclosed, for example, in commonly owned U.S. Patent Application Serial No. 09/798,148, filed on March 2, 2001, and entitled "Fiber For Enhanced Energy Absorption" (now issued as U.S. Patent 6,516,124 on February 4, 2003). In addition, while systems using side pumping have been described, such as in Figs. 5 - 7, other systems can also be used. As an example, systems using end pumping can be used. As another example, systems using both end pumping and side pumping can be used. As yet a further example, Figs. 5 - 7 illustrate optical fibers, such as, for example, optical fibers 10 and 48, that optically communicate. As is understood by one of ordinary skill in the art, an optical connection can include a lens or lenses for conditioning light received from the core of one fiber and providing that light to the core of the other fiber.

[064] Furthermore, while systems having one or two single mode fibers have been described, the invention is not limited in this sense. Additional single mode fibers (e.g., passive single mode fibers) can be used (e.g., three single mode fibers, four single mode fibers, five single mode fibers, six single mode fibers, seven single mode fibers, eight single mode fibers, nine single mode fibers, 10 single mode fibers, 11 single mode fibers, 12 single mode fibers, etc.) following the general principles discussed herein.

Other embodiments are in the claims.